Powering of Future HEP Detectors in 4T & High Radiation - Commercial solutions?

Satish K Dhawan
Yale University

1 Oodle = 10,000 amps
Agenda

- CMS ECAL Powering 2.5 V @ 50,000 amps
- DC-DC Converters: *Reduce Power Supply Currents*
- Commercial Device 100 Mrads- Beginners luck
- ATLAS Upgrade
- Air Coil, Noise tests
- Why Thin Oxide for Radiation
- End of Silicon for Power
- GaN Wide band Gap material. RF & Power Switching
- Industry Developments 400V DC distribution
- Did we find a commercial part for sLHC?
- *Market Trends* Single Chip
- LHC Beam Power Supplies
- Advantage of this development
- Conclusions

Collaborators:

Yale University: Keith Baker, Hunter Smith
Brookhaven National Laboratory: Hucheng Chen, James Kierstead, Francesco Lanni, David Lynn, Sergio Rescia,
CMS ECAL: Electromagnetic Calorimeter

80 Amps Power supply for 4 LVR Boards
Power Supply @6.3V  30 meters away
3K Boards x 16 amps = 48 Kamps
Magnetic Field 4T in CMS
Power Delivery Efficiency < 40 %
CMS Outreach

37 Countries, 155 Institutes, 2000 scientists (including about 400 students)  
October 2006

**Trigger, Data Acquisition & Offline Computing**
- Austria, Brazil, CERN, Finland, France, Greece, Hungary, Ireland, Italy, Korea, Poland, Portugal, Switzerland, UK, USA

**Tracker**
- Austria, Belgium, CERN, Finland, France, Germany, Italy, Japan*, Mexico, New Zealand, Switzerland, UK, USA

**Crystal ECAL**
- Belarus, CERN, China, Croatia, Cyprus, France, Italy, Japan*, Portugal, Russia, Serbia, Switzerland, UK, USA

**Preshower**
- Armenia, CERN, Greece, India, Russia, Taiwan

**Return Yoke**
- Barrel: Czech Rep., Estonia, Germany, Greece, Russia  
  Endcap: Japan*, USA

**Superconducting Magnet**
- All countries in CMS contribute to Magnet financing in particular: Finland, France, Italy, Japan*, Korea, Switzerland, USA

**HCAL**
- Barrel: Bulgaria, India, Spain*, USA  
  Endcap: Belarus, Bulgaria, Georgia, Russia, Ukraine, Uzbekistan  
  HO: India

**Feet**
- Pakistan, China

**Forward Calorimeter**
- Hungary, Iran, Russia, Turkey, USA

**Muon Chambers**
- Barrel: Austria, Bulgaria, CERN, China, Germany, Hungary, Italy, Spain  
  Endcap: Belarus, Bulgaria, China, Colombia, Korea, Pakistan, Russia, USA

* Only through industrial contracts

**Dimensions**
- Total weight: 12500 T
- Overall diameter: 15.0 m
- Overall length: 21.5 m
- Magnetic field: 4 Tesla
CMS ECAL: 5 Oodles (50 Kamps).

- Power Supply output = 315 KW
- Power loss in Leads to SM = 100 KW
- Power loss in Regulator Card = 90 KW
- Power Delivered @ 2.5 V = 125 KW

1 Oodule = 10,000 amps

# of Power Supplies ~ 700
# of ST LDO Chips = 35 K
LHC Radiation Hard made by ST Microelectronics
# of LVR Cards = 3.1 K.

Yale: Designed, built, burn-in and Tested.

Power Delivery Efficiency = 40%
NOT INCLUDED
1. Power Supply efficiency
2. Water cooling
3. Removal of Waste heat
4. Air Conditioning
Power Chain Efficiency for CMS ECAL

Represents the efficiency of power delivery to a physics detector, e.g. ECal

From Experts Efficiency %

Guess work Efficiency %

Power delivery Efficiency
= 30 %

with Power for Heat Removal
= 20 %
What can we do?

• Is there a better way to distribute power?
• High Radiation
• Magnetic Field 4 T
• Load ~1 V Oodles of current
• Feed High Voltage and Convert - like AC power transmission
• Commercial Technologies — No Custom ASIC Chips
• Learn from Semiconductor Industry
• Use Company Evaluation Boards for testing
Type of High to Low Voltage Converters without transformers

- **Charge pumps**
  - Normally limited to integral fractions of input voltage
  - Losses proportional to switch losses
  - Can provide negative voltage

- **Buck Converter – Used in consumer & Industrial Electronics**
  - Needs an ASIC, Inductor and Capacitors
  - Cannot provide a negative voltage
  - Topology allows for more flexibility in output voltage than charge pump
  - Much more common use in commercial applications
Charge Pump: Charge capacitors in series & discharge in parallel

Buck Converter
Energy Stored in an inductor
Synchronous Buck Converter

Controller Low Voltage

Power Stage - High Volts

PWM: Pulse Width Modulator

V reference

Buck Safety

Control Switch: Switching Loss > I^2
Synch Switch: Rds Loss Significant

Minimum Switch ON Time Limits Max Frequency
10 nsec @ 10 MHz

Vout = 11%

Vout = 50%
Buck Regulator Efficiency after 100 Mrad dosage

- Found out at Power Technology conference 0.25 µm Lithography
- Irradiated Stopped on St. Valentines Day 2007
- We reported @ TWEPP 2008 - IHP was foundry for EN5360

Enpirion  EN5360
With Integrated Inductor
LHC Solution

10 Chip Hybrid – SCT Module for LHC

3.5 V
1.5 amps

Cable Resistance = 4.5 Ohms

4088 Cables

10.25 V

Voltage Drop = 6.75 V

sLHC Solution

20 Chip Hybrid – Si Tr Module for Hi Luminosity

1.3 V
2.4 amps

X 4 DC-DC Power Converter

5.2 V

Current Reduced by 4 (losses by 16)

Commercial Solution

EN5360

It is still available

Silicon Technology Limit

(Radiation limited)

20 Chip Hybrid – Si Tr Module for Hi Luminosity

1.3 V
2.4 amps

X 10 DC-DC Power Converter

13 V
0.24 amps

Voltage Drop = 1.08 V

14.08 V

Current Reduced by 10 (losses by 100)

> X 40 with Gallium Nitride Transistors
Power Delivery with Existing SCT Cables (total = 4088)

Resistance = 4.5 Ohms

3.5 V @ 1.5 amps
1.3 V @ 2.4 amps
1.3 V @ 2.4 amps with x10 Buck switcher. Efficiency 90%

Voltage @ Load
Coupled Air Core Inductor Connected in Series

Plug In Card with Shielded Buck Inductor

12 V

2.5 V @ 6 amps

Different Versions

- Converter Chips
  - Max8654 monolithic
  - IR8341 3 die MCM

- Coils
  - Embedded 3oz cu
  - Solenoid 15 mΩ
  - Spiral Etched 0.25mm

Spiral Coils Resistance in mΩ

<table>
<thead>
<tr>
<th></th>
<th>Top</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Oz PCB</td>
<td>57</td>
<td>46</td>
</tr>
<tr>
<td>0.25 mm Cu Foil</td>
<td>19.4</td>
<td>17</td>
</tr>
</tbody>
</table>
**Test @ BNL**

- **Sensor**
- **Inductor**
- **ABCD chips**
- **Only One Chip Bonded**

512 Strips – 100 µm Pitch
51 mm x 84 mm

**Test @ Liverpool**

- **Plug in Card 1 cm from Coil facing Sensor**
- **20 µm Al foil shielding**

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**Noise Tests with Silicon Sensors**

**Input Noise**

<table>
<thead>
<tr>
<th>Coil Type</th>
<th>Power</th>
<th>Input Noise (electrons rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solenoid</td>
<td>DC - DC</td>
<td>881</td>
</tr>
<tr>
<td>Solenoid</td>
<td>Linear</td>
<td>885</td>
</tr>
<tr>
<td>Spiral Coil</td>
<td>DC - DC</td>
<td>666</td>
</tr>
<tr>
<td>Spiral Coil</td>
<td>Linear</td>
<td>664</td>
</tr>
</tbody>
</table>

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**Radiated Noise**

- No Conducted Noise
Threshold Shift vs Gate Oxide Thickness


# CERN ASICs

**Mantra:** Deep sub micron is more rad hard

*Why?*

<table>
<thead>
<tr>
<th>IBM Foundry Oxide Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithography</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>0.25 µm</td>
</tr>
<tr>
<td>0.13 µm</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Can We Have High Radiation Tolerance & Higher Voltage Together ???

Higher radiation tolerance needs thin oxide while higher voltage needs thicker oxide – Contradiction?

Mixed signal power designs from TI, TSMC, IBM etc - 0.18 µm & 0.13 µm Automobile Market. Voltage ratings 10 - 80 Volts Deep sub-micron but thick oxide

Controller : Low Voltage

High Voltage: Switches – some candidates HV & Thin oxide

LDMOS, Drain Extension, Deep Diffusion etc

>> 20 Volts HEMT GaN on Silicon, Silicon Carbide, Sapphire
IHP NMOS Transistor
$V_G$ versus $I_D$ at Selected Gamma Doses

IHP PMOS Transistor
$V_G$ versus $I_D$ at selected Gamma Doses

XY Semi ($VD = 12V$)
2 Amp FET- HVMOS20080720 Process
## Thin Oxide Devices (non IBM)

<table>
<thead>
<tr>
<th>Company</th>
<th>Device</th>
<th>Process</th>
<th>Foundry</th>
<th>Oxide</th>
<th>Dose before</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>IHP</td>
<td>ASIC custom</td>
<td>SG25V GOD</td>
<td>IHP, Germany</td>
<td>12 V</td>
<td>5</td>
<td>Minimal Damage</td>
</tr>
<tr>
<td>XySemi</td>
<td>FET 2 amps</td>
<td>HVMOS20080720</td>
<td>China</td>
<td>12 V</td>
<td>7</td>
<td>Minimal Damage</td>
</tr>
<tr>
<td>XySemi</td>
<td>XP2201</td>
<td>HVMOS20080720</td>
<td>China</td>
<td>15 V</td>
<td>12 / 7</td>
<td>2Q2010</td>
</tr>
<tr>
<td>Enpirion</td>
<td>EN5365</td>
<td>CMOS 0.25 µm</td>
<td>Dongbu HiTek, Korea</td>
<td>5</td>
<td>64 Krads</td>
<td></td>
</tr>
<tr>
<td>Enpirion</td>
<td>EN5382</td>
<td>CMOS 0.25 µm</td>
<td>Dongbu HiTek, Korea</td>
<td>5</td>
<td>111 Krads</td>
<td></td>
</tr>
<tr>
<td>Enpirion</td>
<td>EN5360 #2</td>
<td>SG25V (IHP)</td>
<td>IHP, Germany</td>
<td>5</td>
<td>100 Mrads</td>
<td>Minimal Damage</td>
</tr>
<tr>
<td>Enpirion</td>
<td>EN5360 #3</td>
<td>SG25V (IHP)</td>
<td>IHP, Germany</td>
<td>5</td>
<td>48 Mrads</td>
<td>Minimal Damage</td>
</tr>
</tbody>
</table>

### Necessary condition for Radiation Hardness

**Thin Gate Oxide**

But not sufficient

- IHP: Epi free, High resistivity substrate, Higher voltage, lower noise devices
- Dongbu: Epi process on substrate, lower voltage due to hot carriers in gate oxide
Gallium Nitride Devices Tests 2009

**RF GaN** 20 Volts & 0.1 amp
- 8 pieces: Nitronex NPT 25015: GaN on Silicon
  - Done Gamma, Proton & Neutrons
  - 65 volts Oct 2009

- 2 pieces: CREE CGH40010F: GaN on SiC

- 6 pieces: Eudyna EGNB010MK: GaN on SiC
  - Done Neutrons

**Switch GaN**
- International Rectifier GaN on Silicon
  - Under NDA

Gamma: @ BNL
Protons: @ Lansce
Neutrons: @ U of Mass Lowell

Expose same device to Gamma, Protons & Neutrons
Online Monitoring
Bias during Radiation
Max operating V & I Limit Power by duty cycle

Source

Drain

FET

Gate

30 m

330 2 Watts

1 Ω

Pomona Box

~ 0.070 Amps

Power Supply
V out = 20 Volts

DMM

DC mV

Reading = ~ 0.035 Amps
@ 50% Duty Cycle

0 to - 5 V

D

G

S

GND

50 Ω Terminator

2 Shorted FETs
Rad vs wo Bias

Pulse Generator
0.1 – 2 MHz
50 % Duty Cycle

FET Setup for Proton Radiation Exposure
200 Mrads of Protons had no effect – switching 20 V 0.1 Amp Parts still activated after 7 months
Proton Test
Proton Fluence $=1 \times 10^{15} \text{p/cm}^2$ over a period of about 24 hours.
Biased $= 65$ volts switching @ 1MHz
Average current $= 65$ mA limited by Load resistor. No change in current.

Our next IEEE TNS Paper shall summarize work to date
GaN for Power Switching

- High frequency ~ 10 GHz
- Low Rds & low gate charge > High FOM: Figure of Merit
- High Thermal Conductivity & x10 higher Dielectric strength than Silicon
- No Gate Dielectric!

Figure 1: GaN on silicon devices have a very simple structure similar to a lateral DMOS device and can be built in a standard CMOS foundry
Gallium Nitride Power Devices Tests 2010

Power Devices

- Efficient Power Conversion Corp (EPC) GaN on Silicon
  5 Devices 40 - 200 Volts 3-33 amps. *Sold by Digikey*
  600 V Device samples December 2010

- International Rectifier GaN on Silicon. Announced Feb 2010
  Not yet available for little people with no pockets

Irradiation
Organized by BNL & Yale

Gamma: @ BNL Aug – Sept 2010
Protons: @ Lansce August 2010
Neutrons: @ U of Mass Lowell ??

Irradiation
Organized by Sandia & Yale

Gamma: @ Sandia $
Protons: @ TRIUMF September 2010 $
Heavy Ions: @ TAMU August 2010
EPC9001 #2 Efficiency vs Output Current

Constant Frequency = 566 KHz: Pulse width = 124 - 240 ns:

$V_{out} = 0.95 - 1.34 \text{V}$; $L = 3.9 \mu\text{H}, 4.8 \text{m}\Omega$

- 12V Input Voltage
- 24V Input Voltage
- 36V Input Voltage

---

EPC9001 #2 Efficiency vs Output Current

Constant $t_{wd} = 240 \text{ns}$: Frequency = 164 - 568 kHz

$V_{out} \sim 1.2 \text{V}$; $L = 3.9 \mu\text{H}, 4.8 \text{m}\Omega$

- 12V Input Voltage
- 24V Input Voltage
- 36V Input Voltage

Yale University
May 16, 2010

epc 1015 – 40V: Efficiency with constant frequency and constant on pulse with inputs of 12, 24 & 36 Volts.
EPC9002 #1 Efficiency vs Output Current

- **Constant Frequency** = 496 kHz: **Pulse width** = 100 - 173 ns:
  - $V_{out} = 1.2015 - 1.857 \text{ V}$
  - $L = 3.9 \mu \text{H}$
  - $R = 4.8 \text{ m\Omega}$

- **Constant Frequency** = 266 kHz: **Pulse width** = 166 - 358 ns:
  - $V_{out} = 1.7984 - 1.8144 \text{ V}$
  - $L = 3.9 \mu \text{H}$
  - $R = 4.8 \text{ m\Omega}$

Need better GaN drivers preferably integrated on the wafer.
Set up with Resistor Load (Alternate is Active Load)
Powering ILC SiD Detector
Air Coil DC-DC Converter
Vin 12 V
Plug in card
Maxim / IR
3 meters Twisted pair AWG 24

Enable Gate
ON: 0.8 µs
OFF: 10 µs

Yale University
May 30, 2010

Air Coil DC-DC Converter
Pulsing Load

Plug in card
Maxim / IR

Vin 12 V

3 meters Twisted pair AWG 24

Enable Gate
ON: 0.8 µs
OFF: 10 µs

Load Resistor
2.5 Ω 10 W

Turn off Spike with
1 amp load = 27 V
FWHM = 80 nS

+2.5 V Bump = 200 mV

Load = 3 amps (Electronic)

Pulsing Converter

Load = 3 amps (Electronic)

Enable Gate

Vout = 2.5 V

KPiX
ASIC Chip

Converter

SiD Powering Pulsing

Pulsing Converter

Analog - Long Time constants, Slow Settling

Power Switch

Vin P

Gate

Power Switch

Analog - Fast Settling

Digital

Power Switch
## Status of GaN player

<table>
<thead>
<tr>
<th>Company</th>
<th>Detail of Target or status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fujitsu Laboratory</td>
<td>Mass-production level in 2011(fiscal)~2012 in the medium Vb over 600V using Si or SiC substrate (representative by Fujitsu Micro-elect.)</td>
</tr>
<tr>
<td>Furukawa and Fuji Electric</td>
<td>Commercial use at 2011(fiscal)</td>
</tr>
</tbody>
</table>
| International Rectifiers      | Commercial use from 2010
Beginning of product is lower Vb such several tens of voltage |
| NEC (Renesus)                 | Deliver Sample at 2011(fiscal)                                                           |
| Panasonic                     | Commercial use at 2011(fiscal)                                                           |
| Rohm                          | Deliver Sample at 2011(fiscal), also developing GaN native substrate                     |
| Sanken Electric               | Trial manufacture of Vb over 800 V                                                       |

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From Nikkei electronics (2010.1.11 in Japanese)

- Velox (Developing SBD with STMicro)
- IR (Announcement of establish 6in-line)
- EPC announced GaN devices on Si
  - Fujitsu (At DRC2009, massproduction at 2011 using 6in-line)
  - NEC (paper at IEDM2009)
- Advanced power device research association (Furukawa & Fuji)
- Sanken-electric or Panasonic have been developing the GaN devices going to massproduction at 2012
Fig. 8 Chip photograph of fabricated GaN monolithic inverter IC in which 6 GITs are integrated.

Panasonic IEDM Motor Driver: Green Air Conditioners
Server Power System Distribution from IBM

1. AC Distribution - 208/230/115V
   - Servers, Blade Servers, Workstations
2. 12V DC Distribution
   - Blade Server Chassis, Low end and Midrange Servers, Workstations
3. 48V Distribution in a Rack
   - High End Server Applications
4. 350V DC Distribution in a Server Rack or a Rectifier Cabinet
   - Main Frame Servers

What is happening outside HEP?

International Workshop on Power Supply On Chip
Sept 22nd - 24, 2008
October 13-15, 2010
Cork, Ireland

Average Efficiency for 12V – 1.XX VRM

Potential LV DC-DC Power Stage Roadmap
Optimized Performance – Without tradeoff

Based on Circuit Simulation
AC - DC Power Efficiency Challenge by IBM September 2007

**Diagram:**

- **Front End Supply (FES):** 240 Vac to 400 Vdc
- **Intermediate Bus Supply (IBS):** 400 Vdc to 12 Vdc (via ac-dc and dc-dc converters)
- **Point of Load (POL) Supply:** 12 Vdc to 1.2 Vdc (via dc-dc converter)
- **Final Output:** uP

**Table:**

<table>
<thead>
<tr>
<th></th>
<th>FES</th>
<th>IBS</th>
<th>POL</th>
<th>Plug-to-Processor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recent</td>
<td>93%</td>
<td>95%</td>
<td>88%</td>
<td>78%</td>
</tr>
<tr>
<td>Best Immediate</td>
<td>95%</td>
<td>98%</td>
<td>90%</td>
<td>84%</td>
</tr>
<tr>
<td>IBM Challenge</td>
<td></td>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>Needed</td>
<td>98%</td>
<td>98%</td>
<td>94%</td>
<td>90%</td>
</tr>
</tbody>
</table>
CONVERTERS INSTALLED

CERN - Chamonix 2010 Report

- LHC CONVERTERS VS RADIATION [2010]
  - Rad Tolerant Design or standard Design with low Rad sensitivity (safe components)
  - Standard Design and Rad sensitivity unknown (too many components, sub-assemblies...)

<table>
<thead>
<tr>
<th>Converter Type</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC120A-10V</td>
<td>191</td>
</tr>
<tr>
<td>LHC600A-10V</td>
<td>272</td>
</tr>
<tr>
<td>LHC600A-40V</td>
<td>25</td>
</tr>
<tr>
<td>LHC4..8kA-08V</td>
<td>16</td>
</tr>
<tr>
<td>LHC13kA-180V</td>
<td>8</td>
</tr>
<tr>
<td>LHC13kA-18V</td>
<td>16</td>
</tr>
<tr>
<td>LHC60A-08V</td>
<td>752</td>
</tr>
</tbody>
</table>

Is it possible to do this Power Train in GaN? Investigate ????

60 A @ 8 V  752 units

Radiation Risk

20/10/2010
Thurel Yves
Review of the radiation tolerance of LHC power converters

Date: April 13 -14 2010
Reviewers: Bill Bartholet, Boeing (Email: bill.bartholet@boeing.com ). Jorgen Christiansen, CERN/PH-ESE (Email: Jorgen.christiansen@cern.ch ). Federico Faccio, CERN/PH-ESE (Email: Federico.Faccio@cern.ch ). Rémi Gaillard, Consultant (Email: gaillardremi@wanadoo.fr ). Bob Lambiase, BNL (Email: lambiase@bnl.gov ). Rick Tesarek, Fermilab (Email: tesarek@fnal.gov ). Kay Wittenburg, DESY (Email: kay.wittenburg@desy.de ). Prevented to be present in review meeting: Claudio Rivetta, SLAC (Email: rivetta@slac.standford.edu ).
Source of Material: http://indico.cern.ch/internalPage.py?pageId=0&confId=85477

Executive summary: This review of the radiation tolerance of the power converters for the LHC accelerator concludes that the current power converters at their current locations introduces a significant risk for the reliable running of the LHC at high luminosities. At nominal LHC luminosity it can be estimated that radiation induced transient and destructive failures in the power converters might seriously limit the beam availability for physics.

For the initial 1st physics run (2010 -2011), at low luminosity, the currently implemented shielding improvements is estimated to allow the current power converters to have sufficient reliability. There is in practice no other alternative, as no major improvements can be introduced during the running period.

For the planned 2nd physics run (2013-2014), at increased luminosity and increased energy, radiation induced failures can become a limiting factor for the running of the accelerator (directly dependent on luminosity). Because of the limited time available only minor incremental improvements can in practice be implemented to improve this (relocation, improved shielding and minor power converter modifications). It is proposed to perform a paper vulnerability analysis of the current power converters as soon as possible. Part-level radiation tests of identified high risk components can then be made to determine where such improvements can be implemented to reduce the global risk.

For the long term running at full nominal luminosity the current power converters can be expected to become a serious limitation for the effective running of the accelerator. They should therefore be replaced by new radiation tolerant converters or the current converters must be relocated to areas without radiation. The design and production of new radiation tolerant power supplies will require a significant time and should therefore be started as early as possible.
Conclusions

• The power distribution needs of HEP detectors require new solutions/technologies to meet power and environmental requirements.
• DC/DC (Buck) Converters are potential solutions for these needs.
• The environment requires that these converters operate in high radiation environments and high magnetic fields at high switching frequencies in a small size/mass package.
• Target technologies for the switches are radiation hard GaN and 0.25 \(\mu\)m LDMOS. High frequency controllers driving small sized nonmagnetic/air core inductors are also required.
• Many of these components have been tested and now need integration to produce a working prototype. This is the next step in our R&D program.
What can be achieved by this Development?

- Current Reduction from Power Supply by DC-DC near Load
  Losses > \( \text{Current}^2 \times \text{Resistance} \)

- Silicon \( \div 10 \) Current Reduction 5 Oodle > 0.5 Oodle
  
  *Power Loss reduced by 100*

- GaN \( \div 50 \) Current Reduction 5 Oodle > 0.1 Oodle
  
  *Power Loss reduced by 2500*

  Power Converters for Beam Line usage ??

**Thermal Challenge**

- A grain of Basmati Rice
  - 4 watts

- GaN FETs
  - 40 V 33 A 4m\( \Omega \)

- FET Solder side
Top of the World is Cool but lonely! Let us keep it cool with highly efficient PS.
Swimming is Great at the North Pole.

More Details: http://shaktipower.sites.yale.edu/